A Climatic Sand Management Model for Cardiff State Beach, CA

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May 13, 2023

Abstract

An empirically based sediment budget model is developed for Cardiff State Beach CA to assess management strategies to maintain beach width subject to mean sea level rise (MSLR) and potentially more frequent El Niño storms. Two decades (2000-2019) of surveys support the hypothesis that the rocky reefs bounding this beach retain sand added to the nearshore zone, except during strong El Niño years with more severe storm waves. The subaerial beach has widened by ~60 m during the last 20 years owing to nourishment (~17K m3/yr) of imported sand, and sand bypassed annually by dredging a lagoon inlet at the beach's updrift end. The observed widening yields 1 m/yr of mean beach width increase for each 6 m3/m-shoreline of added sand. A strong El Niño year is modeled with a permanent volume loss coupled with a shoreline retreat that recovers partially as the beach profile adjusts between El Niño years. Calibrated with observations from Cardiff and South Torrey Pines (a control beach), the model is used to project beach change through 2050. All modeled scenarios suggest that no bypassing or nourishment (no "management") will result in tens of meters of beach width loss. However, continued bypassing would partially mitigate MSLR and El Niño beach width losses. An artificially built (living shoreline) dune that backs the beach, if completely undermined during strong El Niño storm waves, stores enough sand to balance one-third of the expected volume loss that year, and may make the beach more resilient and speed subsequent beach recovery.

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Key Points:

- A sediment budget model is developed for Cardiff State Beach CA to assess management strategies to maintain beach width in the future.
- The factor of three uncertainty in mean sea level rise by 2050 creates correspondingly large uncertainty in projections of beach width.
- All modeled scenarios suggest that continued bypassing would at least partially mitigate sea level rise and El Niño beach width losses.

Abstract

An empirically based sediment budget model is developed for Cardiff State Beach CA to assess management strategies to maintain beach width subject to mean sea level rise (MSLR) and potentially more frequent El Niño storms. Two decades (2000-2019) of surveys support the hypothesis that the rocky reefs bounding this beach retain sand added to the nearshore zone, except during strong El Niño years with more severe storm waves. The subaerial beach has widened by ~60 m during the last 20 years owing to nourishment (~17K m^3/yr) of imported sand, and sand bypassed annually by dredging a lagoon inlet at the beach's updrift end. The observed widening yields 1 m/yr of mean beach width increase for each 6 m^3/m-shoreline of added sand. A strong El Niño year is modeled with a permanent volume loss coupled with a shoreline retreat that recovers partially as the beach profile adjusts between El Niño years. Calibrated with observations from Cardiff and South Torrey Pines (a control beach), the model is used to project beach change through 2050. All modeled scenarios suggest that no bypassing or nourishment (no "management") will result in tens of meters of beach width loss. However, continued bypassing would partially mitigate MSLR and El Niño beach width losses. An artificially built (living shoreline) dune that backs the beach, if completely undermined during strong El Niño storm waves, stores enough sand to balance one-third of the expected volume loss that year, and may make the beach more resilient and speed subsequent beach recovery.

Plain Language Summary

A beach sediment budget refers to sediment volume gains and losses over time in a defined area with sediment sources and sinks. Here, a sediment budget model is developed for Cardiff State Beach, CA that projects future mean beach widths considering both sea level rise and an increased frequency of strong El Nino storms. This model is used to assess management strategies to maintain beach width in the future through 2050. Past observations on the beach demonstrate that the beach has widened by ~60m during the last 20 years owing to addition of imported sand ("nourishment") and sand from annual dredging of the lagoon inlet ("bypassing") at the north end of the beach. Using these observations and others at nearby beaches, the model is used to project multiple scenarios for the beach: The no bypassing or nourishment (no management) will result in tens of meters of beach width loss. However, continued bypassing would partially mitigate beach width losses. An artificial dune (living shoreline) that backs the beach, if completely undermined during strong El Niño storm waves, stores enough sand to balance one-third of the expected volume loss that year, and may make the beach more resilient and speed subsequent recovery.

1 Introduction

US West Coast beach sand management practices will increasingly contend with MSLR and potentially more frequent El Niño winter storm conditions as the climate warms. Sea levels have risen by 0.2 m over the past century, with 0.1-0.3 m increases projected by 2050 (Sweet et al, 2022). El Niños are typically defined as moderate or strong (Takahashi and Dewitte, 2016) and strong El Niños have intensified since 1970 (Grothe et al, 2020). A comprehensive assessment of El Niño-Southern Oscillation (ENSO) climate change (Cai et al, 2021, Ying et al, 2022) suggests that extreme ENSO events may also increase in frequency. Vos et al (2023) describe

ENSO as "the dominant mode of interannual climate variability, driving substantial changes in oceanographic forcing and impacting Pacific coastlines".

Intra-annual and long-term beach width changes, particularly beach retreat, have serious negative consequences for coastal recreation, infrastructure, habitats and ecosystems. Reliable, quantitative projections of near- and long-term coastal changes are critical to coastal management and adaptation. Southern California beaches have been sustained, enhanced, and stabilized for over a century through (1) nourishment sand derived mainly from wetland and harbor dredging and other large coastal development works, and (2) sediment retention devices, consisting mainly of groins, but also including a few offshore breakwaters and harbor and lagoon mouth jetties (Johnson 1935, O'Brien 1936, Herron 1980, Flick 1993, Flick and Ewing, 2009, Anderson et al. 2020). More recently, nature-based solutions such as living shoreline elements have been incorporated into coastal resilience designs (e.g. Kochnower et al. 2015, Saleh and Weinstein 2016, Winters et al. 2020, Portner et al, 2022). During the last twenty years, several approaches have been implemented at Cardiff State Beach in Encinitas, CA.

A beach sediment budget refers to the summed sediment volume gains and losses over time in a defined geographic area, often referred to as a littoral cell, with sediment sources and sinks (Bowen and Inman, 1966; Komar, 1996; Rosati, 2005; Patsch and Griggs, 2006; List, 2018). For coastal managers, sediment budgets clarify if beaches within a littoral cell are eroding (inflow < outflow), accreting (inflow > outflow), or stable. Typical sediment sources include rivers, cliffs, dunes, and sand nourishment (artificial placement of sand on beaches). Sediment sinks include longshore or offshore wave-driven transport out of the cell, and landward wind transport.

Here, we develop a climatic sediment budget model for Cardiff State Beach (Cardiff) that projects future nearshore sediment volumes and annual mean beach widths considering both MSLR and an increased frequency of strong El Niño storms. Cardiff is treated as a "closed" system or sub-cell of the larger Oceanside littoral cell. The working assumption that net southward sediment output from the Cardiff sub-cell is zero during post-El Niño beach recovery is justified by 2010-2015 observations at Cardiff (Section 2) where the increase in nearshore volume is balanced by reported nourishment and bypass volumes, indicating retention of nearshore sand (Supporting Information S1). The simplified modeling approach is data-driven and assumes underlying equilibrium profile behavior with a one-to-one relationship between changes in annual sand volume and mean beach width (Fletcher et al., 2003, Davidson et al., 2013, Ludka et al., 2015, Vitousek et al., 2017).

In Section 2 we describe surveys of Cardiff, a 1.7 km-long steadily nourished beach that has widened considerably (+60 m) since 2000. A seasonally weighted survey data reduction methodology is used to estimate annual beach widths and volumes. The observed annual mean nearshore volume increased by 153K m^3 from 2010 to 2015, mirroring the total reported added volume of 158K m^3; 68K m^3 nourishments and 90K m^3 bypassing (SANDAG, 2021). Volume and beach width changes observed from 2010-2016 at Cardiff, and 2010-2014 at the South Torrey Pines unnourished control beach (10 km south of Cardiff) are used to estimate model source-sink terms (Section 3). Beach width change owing to MSLR assumes a constant annual mean shoreface slope and equilibrium profile behavior but does not explicitly follow Bruun (1962, Supporting Information S2). In Section 3.5, the sediment budget model is applied to Cardiff surveys for 2000-2019. Section 4 contains model projections for 2020-2050 using ENSO and future MSLR scenarios. Model assumptions, limitations, and additional sediment management considerations are in Section 5.

2 Site Description and Observations

Cardiff is a 1.7 km-long former barrier bar (now a further-elevated roadway stabilized by rip-rap), gently sloping, sandy beach in San Diego County along the west side of San Elijo Lagoon (Figure 1c). Cardiff is bounded in the north by Cardiff Reef and in the south by Seaside/Tabletop Reefs, elevated bedrock that function as submerged groins.

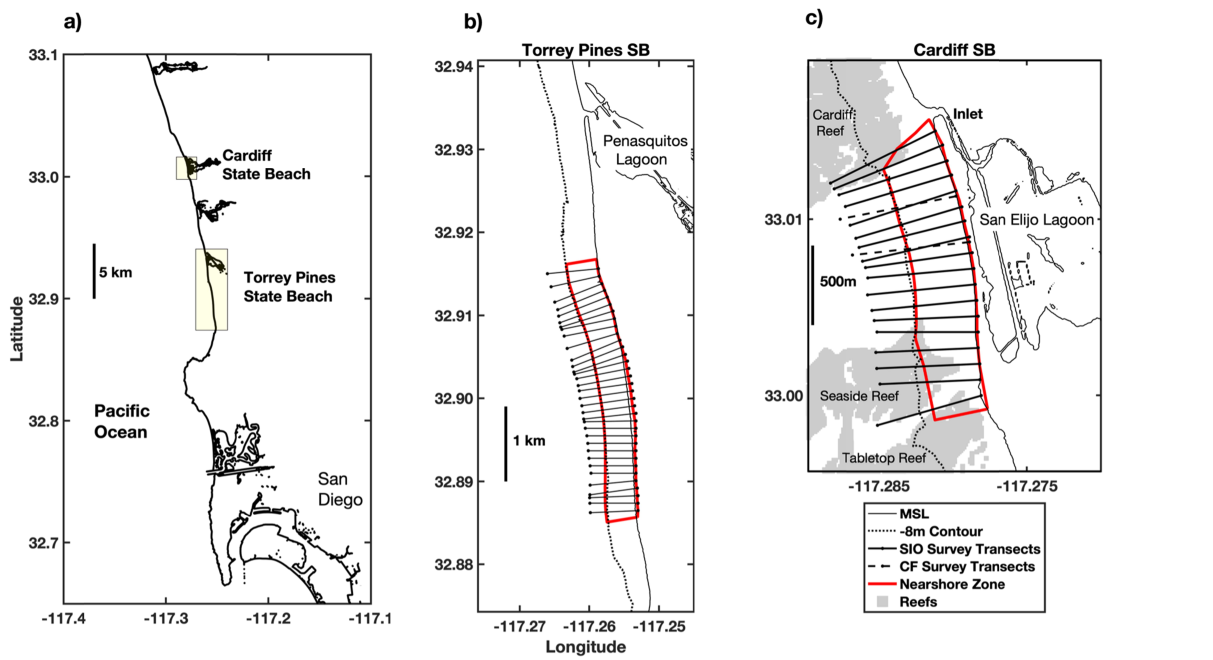

Fig. 1. (a) Locations of Torrey Pines and Cardiff State beaches in San Diego County, CA. **(b)** South Torrey Pines SIO survey transects (solid lines). **(c)** Cardiff SIO (solid lines) and Coastal Frontiers (CF, dashed lines) survey transects. The nearshore zone (red boxes), used for annual mean beach width and volume estimates (Fig. 3), extends from the back beach to about 8m depth. Cardiff is bounded alongshore by reefs (shading) and onshore by dunes, Hwy 101 (see Fig. 2) and San Elijo Lagoon (inlet located at the northern end of the beach).

The San Elijo Lagoon inlet, fixed at the north end of the beach, is typically dredged each spring to maintain exchange of lagoon and ocean water. Dredged sand is mechanically "bypassed" south (downdrift) and placed on the subaerial beach, or in shallow water (Table 1*)*. Dredging enhances entrainment of southward littoral drifting sand into the inlet during winter. Similar sand bypassing has been historically used to recycle sediment trapped by lagoon entrances or other features in San Diego County (SANDAG, 2021).

Year	Bypass (m^3 x 1000)	Nourishment (m^3 x 1000)	Nearshore V (m^3 x 1000)
2000	18	0	-
2001	18	77	-
2002	14	0	-
2003	24	0	-
2004	23	0	-
2005	13	0	-
2006	14	0	-
2007	15	0	495
2008	18	0	495
2009	15	0	507
2010	16	0	518
2011	18	0	551
2012	18	68	595
2013	20	0	642
2014	18	0	678
2015	17	0	671
2016	17	0	612
2017	13	0	593
2018	8**	229*	659
2019	11**	0	726

Table 1 : Annual volumes (1,000s of m^3) of bypass and nourishment sand (SANDAG, 2021) and estimated annual mean nearshore volumes from SIO surveys (17 transects) 2007-2019. ** The reported 2018 nourishment volume estimate of the San Elijo Lagoon Restoration Project, was approximately 2x larger than the surveyed nearshore volume increase during 2017-2019. ** Bypassing sand used in the construction of the living shoreline dune.*

The artificial Cardiff living shoreline dune (Fig. 2) was built adjacent to Hwy 101 in 2019 and contains about 20K m^3 of sand and cobbles (Winters et al, 2020). The dune height exceeds the elevation of the natural wave-deposited back beach terrace elevation (red line, Fig. 2) and protects Hwy 101 from wave runup and flooding. From a sediment budget perspective, the dune represents "stored" sediment that is added to the active nearshore system when the dune erodes during severe winters.

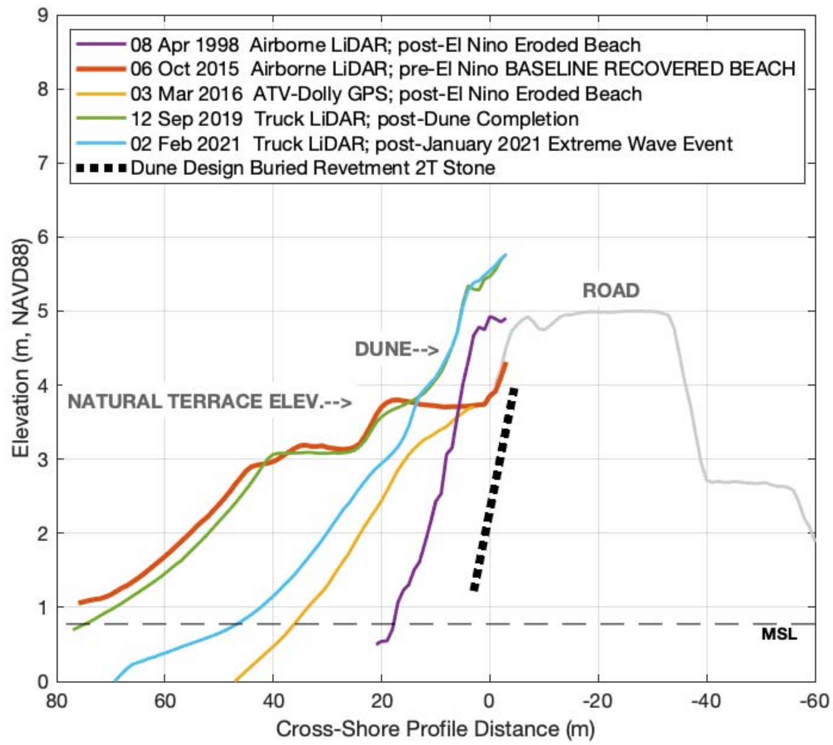

Fig. 2. Beach elevation versus cross-shore distance near the center of Cardiff Beach. The living shoreline dune (blue and green profiles above the natural terrace elevation) and the approximate location of buried stone armoring at the base of Hwy 101 (bold dashed) are shown. The severely eroded post-1997-98 El Niño winter profile (purple) is likely cobbles.

2.1 Beach and Nearshore Surveys

Subaerial and subaqueous cross-shore profiles were surveyed at least quarterly at South Torrey Pines (since 2003) and Cardiff (since fall 2010) by the Scripps Institution of Oceanography (SIO, Ludka et al, 2019). A GPS-equipped ATV (exposed, dry beach), hand-pushed dolly (swash zone), and jetski (to 8-m depth) were used to collect two types of sand elevations along transects spaced 100m in the alongshore: "Subaerial Beach only" (ATV), and "Nearshore" (ATV-dolly-jetski) extending from the back beach to 8 m depth. Truck-mounted LiDAR was used for beach-only surveys beginning in 2017. The South Torrey Pines/Cardiff survey regions span about 3,300 m/1,700 m alongshore and 400 m/500 m cross-shore, respectively (Fig. 1b,c).

Semi-annual cross-shore profiles on many San Diego County beaches were collected since 1996 by Coastal Frontiers Corporation (CF) as part of the San Diego Association of Governments (SANDAG) regional beach monitoring program (SANDAG, 2021). CF uses GPS-equipped dry beach and deep-wading survey pole methods in combination with inflatable vessels. We use CF data for two Cardiff transects (located near the beach middle (dashed lines, right panel, Fig. 1c).

2.2. Annual Mean Nearshore Volume and Beach Width Estimates

SIO Beach-only and portions of the Nearshore surveys are each gridded and reduced progressively to mean monthly grids, mean quarterly (seasonal) grids (derived from the mean monthly grids), and finally mean annual grids (derived from the mean quarterly grids). With this merging, time periods of frequent surveying are appropriately de-weighted when estimating longer-term volumes.

A mean annual grid represents a complete "beach year" from fall (end of summer)-to-fall (12 months from Oct-Sep). A beach year contains grids from the last quarter of the previous calendar year and first three quarters of the "beach year". The area with co-located data across all the annual grids is defined as the nearshore zone for estimates of annual nearshore volume change and beach width (Table 1, red boxes, Fig. 1b-c).

Annual mean nearshore volumes (Fig. 3a) are "known to be mobile" estimates relative to a global minima surface derived from all gridded surveys. SIO annual mean beach widths (Fig. 3b) are the mean cross-shore distance between the nearshore zone landward boundary and the mean sea level (MSL) contour in the annual mean grids. CF annual mean beach widths are the annual average of MSL cross-shore distances from both CF Cardiff profile locations, a total of four values each year for the semi-annual surveys, adjusted by +9.7 m in the cross-shore to match the SIO nearshore zone landward boundary (Fig. 3b).

The observed width and volume at South Torrey Pines and Cardiff from 2010-2015 (recovery from the 2010 El Niño) and before the 2016 strong El Niño, are used to quantify sediment budget model terms in Section 3. The South Torrey Pines observations are used to estimate ENSO recovery cycle beach width growth between El Niños when there is constant nearshore volume. No sand was added to this beach in 2010-2014, the nearshore sand volume was relatively stable (Fig. 3a), and a multi-year annual mean beach width recovery occurred (4m over 5 years, Fig. 3b). We assume this width recovery is from net shoreward sand migration *within* the system. The Cardiff observations are used to relate beach width changes to nearshore volume changes. During the 2010-2015 ENSO recovery at Cardiff, the observed volume change (153K m^3) and cumulative additions (158K m^3) are of similar magnitude (Fig 3a) suggesting that the Cardiff nearshore zone retained the annual bypassing and 2012 nourishment sand (Supporting Information S1). In addition, the Cardiff observations are used to estimate the net nearshore volume loss associated with the strong 2016 El Niño (pink shading, -59K m^3, Fig 3a).

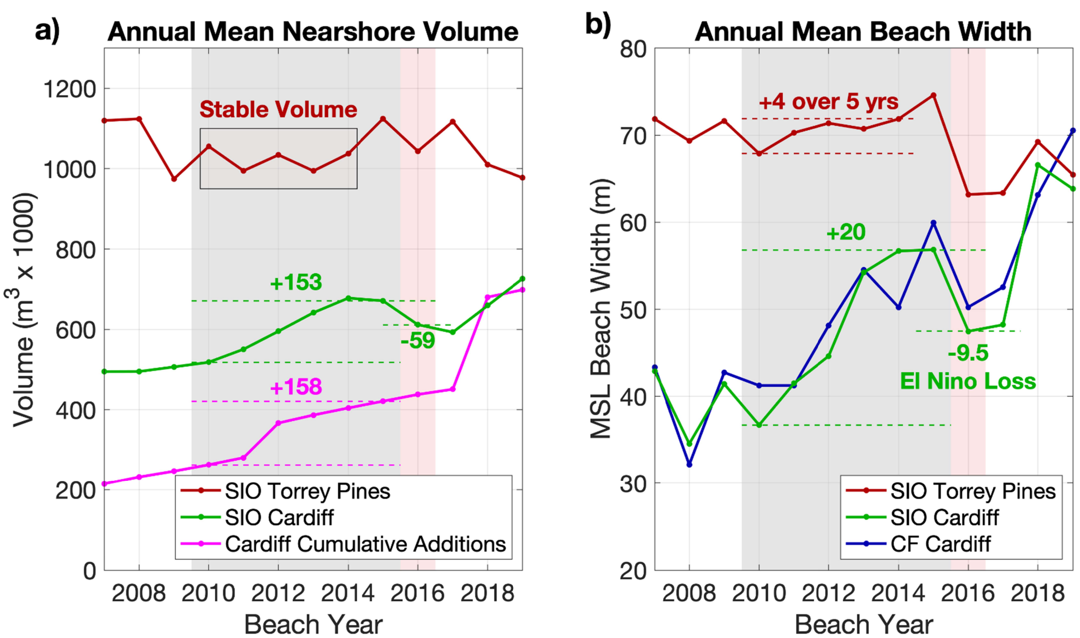

Fig. 3. SIO survey based estimates at South Torrey Pines (red) and Cardiff (green) of annual mean (a) nearshore volume and (b) beach width. CF beach widths (blue) are offset +9.7 m to match the SIO back beach reference frame. 2010-2015 (gray shaded) were recovery years prior to 2016 (red shaded) El Niño year. Noted volume and beach width changes are used to define budget model terms (Section 3).

3 Climatic Sediment Management Model

The annual mean beach width relative to mean sea level, $\underline{X}_{MSL}$, is the physical beach metric to be monitored, modeled, and managed. Sediment transport paths contributing to beach width change are shown schematically in Fig. 4. The yearly change in mean beach width location $\Delta\underline{X}_{\mathrm{MSL}}$ (Eq. 1) is the sum of 1) change to the total nearshore sand volume 2) ENSO-driven multi-year cross-shore migration of sand *within* the survey area, and 3) MSLR.

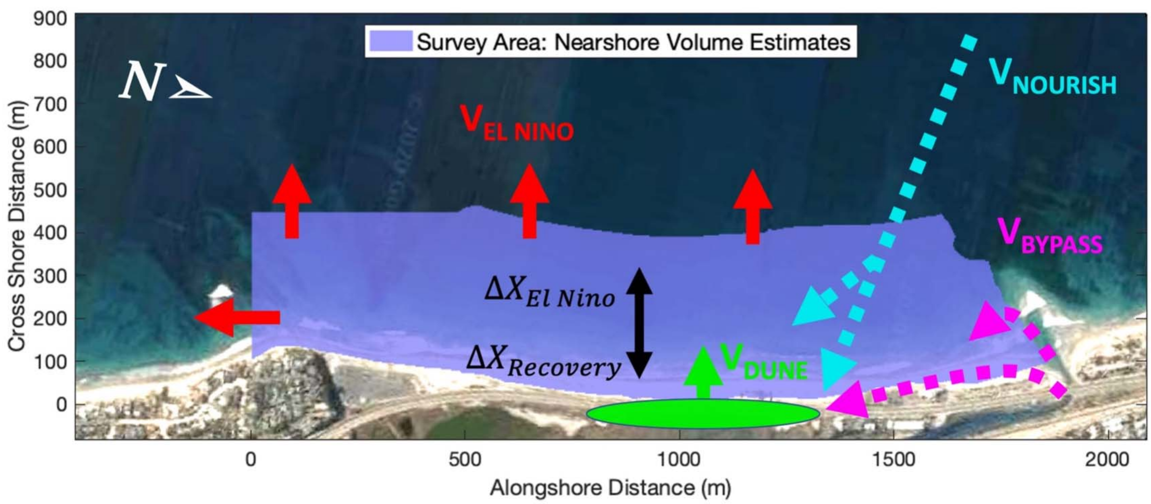

Fig. 4. Schematic of model sediment transport paths contributing to beach width change (Eq. 1) at Cardiff. Bypassed sand volume (V_{Bypass}) is dredged from the inlet channel and placed in the active nearshore zone or stored in the dune. Additional nourishment sand ($V_{Nourish}$) from remote sources can also supply the nearshore and dune. Sand is both lost from the active nearshore zone during a strong El Niño ($V_{El\ Niño}$) and added via dune erosion (V_{Dune}). $\underline{X}_{ElNiño}$ *and* $\Delta\underline{X}_{Recovery}$ govern the moderate ENSO cycle beach width loss and recovery that does not involve any nearshore volume change.

(1) $$\Delta\underline{X}_{MSL} = C_{Equil} \cdot [\Delta V_{Bypass} + \Delta V_{Nourish} - \Delta V_{ElNiño} + \Delta V_{Dune}] + [-\Delta\underline{X}_{ElNiño} + \Delta\underline{X}_{Recovery}] - \Delta Z_{SL}/\beta_{SL}$$

↖ ↑ ↑ ↗ ↑ ↑ ↑

Nearshore Volume Change *ENSO Cycle* *Sea Level Rise*

Retreat and Recovery *(Retreat)*

where $\Delta V_{[\,]}$ are yearly sediment volume source/sink change terms, $\Delta\underline{X}_{[\,]}$ are ENSO shoreline retreat (El Niño years) and recovery (non-El Niño years) terms, ΔZ_{SL} is yearly sea level rise, and β_{SL} is the mean shoreface slope. $\Delta V_{[\,]}$ is assumed to result in a new underlying annual mean equilibrium profile shape, and C_{Equil} (units m^{-2}) is the ratio of mean beach width change to total nearshore volume change, $\Delta\underline{X}_{MSL}/\Delta V$. The model (Eq. 1) predicts yearly beach width change using "beach years" (Oct-Sep), following the seasonal erosion-accretion beach cycle.

3.1 $\Delta V_{[\,]}$, Nearshore Sediment Volume Changes

Nearshore volume changes ($+\Delta V_{Bypass}$, $+\Delta V_{Nourish}$, $+\Delta V_{Dune}$, $-\Delta V_{El\ Niño}$) are annual model boundary conditions that can be varied each year to represent specific climate, sand management plan and dune maintenance scenarios (eg. Fig 6b).

3.1.1 Volume Additions

ΔV_{Bypass} [historically +8K to +24K m^3/yr] is the annual bypass volume from San Elijo Lagoon inlet (Table 1). Bypass sand is assumed to come from either the lagoon (e.g. inland sources) or downcoast from the north. $\Delta V_{Bypass} = 0$ in the year(s) after a strong El Niño if the bypass sand is used to rebuild the eroded dune instead, and is not considered as a volume addition to the beach width sand budget until the next strong El Niño, where it appears as part of ΔV_{Dune}.

$\Delta V_{Nourish}$ [historically +68K to +229K m^3, various years] are less frequent non-bypass nourishment volumes placed seaward of the living shoreline dune (Table 1). It includes the SANDAG Regional Beach Sand (RBSP I) in 2001 (77K m^3) and RBSP II in 2012 (68K m^3) and an estimated 229K m^3 in 2018, although this amount has not been fully accounted for in the subsequent surveys. As with ΔV_{Bypass}, any non-bypass nourishment sand used to rebuild the eroded dune is not considered as a volume addition to the beach width sand budget until the next strong El Niño, where it appears as part of ΔV_{Dune}.

ΔV_{Dune} [+20K m^3, strong El Niño years only] is added to the nearshore zone sand budget in strong El Niño years only, when the living shoreline dune is assumed to be completely undermined by winter waves (Fig. 2). It is defined as sand above the natural beach terrace elevation of the fully accreted beach observed on Oct 6, 2015 at the end of the beach recovery between the 2010 and 2016 El Niño winters (red line, Fig. 2, prior to the construction of the living shoreline dune). Eroded profiles from the 1998 and 2016 strong El Niño winters (purple and yellow curves, Fig. 2) suggest the dune will be undermined during a strong El Niño, adding some or all stored sand to the active beach. Any bypass or nourishment sand volume used to rebuild the living shoreline dune in subsequent years is withheld from the nearshore zone sediment budget until the next strong El Niño, where it appears as part of ΔV_{Dune}. $V_{Dune} \sim$ 22K m^3 based on the January 2022 truck LiDAR survey relative to the Oct 2015 baseline survey, close to the ~23K m^3 of native dredged sand used between November 2018 and June 2019 (SANDAG, 2021). We use V_{Dune} = 20K m^3.

3.1.2 Volume Subtractions

$\Delta V_{El\ Niño}$ [-76K m^3 , strong El Niño years only] is sand that migrates out of the Cardiff nearshore zone during strong El Niño year winter wave events (eg. 2016) and is assumed permanently lost offshore or to the south over Seaside and Tabletop Reefs. For all other years, La Niñas to moderate El Niños, $\Delta V_{El\ Niño} = 0$, as the nearshore volume did not change significantly during the moderate 2010 El Niño (green line, Fig. 3a). The strong El Niño loss estimate is derived from the observed *net* change in nearshore volume between 2015 and 2016 (-59K m^3, green line, Fig. 3a) adjusted for the concurrent positive bypass contribution of 17K m^3 in 2016 (Table 1).

3.2 C_{Equil} , Beach Width Change vs. Nearshore Volume Change

Equilibrium profile theory is assumed to underlie the evolution of the mean beach width on annual time scales as sand is added and subtracted from the nearshore zone. The ratio of mean sea level beach width change to total nearshore volume change,

(2) $C_{Equil} = \Delta \underline{X}_{MSL} / \Delta V_{Nearshore}$; for Cardiff, C_{Equil} =15m/158K m^3 = 9.5 x 10^{-5} m^{-2}

is key for budget-based shoreline change modeling (Bodge, 1998; Norcross et al., 2002). C_{Equil} is difficult to model because it depends on the unknown redistribution of sediment in the evolving annual mean profile shape when the volume changes. For simplicity, Bruun (1962) assumes volume changes are equally distributed across the entire active profile on interannual timescales, but supporting observations are lacking and the predicted profile discontinuity at the offshore end of the hypothetical active profile is problematic. Therefore, Bruun (1962) provides only a rough approximation. Here, we estimate C_{Equil} at Cardiff with yearly averaged observations of shoreline location and the nearshore sand volume.

At Cardiff, the significant annual additions of sand to the nearshore zone, and the unusual extent to which sand appears to be retained by the shallow reefs at its boundaries most years (Supporting Information S1), provides a unique opportunity to estimate C_{Equil}. By subtracting the expected ENSO-driven beach width behavior, as observed between 2010-2014 at unnourished South Torrey Pines (+5 m of recovery beach width over 6 years when extrapolating the 4 m/5 yr result, red line Fig. 3b) from the larger observed changes at nourished Cardiff (+20 m, green line, Fig. 3b), the remaining beach width change ($\Delta \underline{X}_{MSL}$= +15 m) is assumed to be the mean equilibrium profile response to the added sand volume ($\Delta V_{Nearshore}$= +158K m^3). C_{Equil} = 15m/158K m^3 = 9.5 x 10^{-5} m^{-2} translates to ~1 m annual mean beach width per ~10,500 m^3 of added nearshore volume, or more generally, ~1 m beach width per ~6 m^3/m-shoreline of added volume (10,500 m^3/1,700 m-long beach).

Bruun (1962, Supporting Information S2) also defines an equivalent beach width to nearshore volume ratio

(3) $C_{Bruun} = \Delta \underline{X}_{MSL} / \Delta V = 1 / [\,(h + B) \cdot Y\,] = 1/[(10+2) \cdot 1{,}700] = 4.9\ x\ 10^{-5}$ m^{-2} for Cardiff,

where h = 10 m is the active profile depth, B = 2 m is berm height, and Y = 1,700 m is the beach alongshore length. Thus $C_{Bruun} \sim C_{Equil}/2$ and Bruun (1962) predicts smaller changes in mean beach width (both positive and negative) compared with Cardiff observations between 2010-2016 (Fig. 6a). An "effective" active profile height (h+B) = 6.25 m is required for C_{Bruun} to match C_{Equil}, significantly lower than used in practice.

For C_{Equil} , mobile nearshore sand volume changes are assumed to lead to changes in equilibrium-seeking profile behavior over the course of the year, which in turn leads to changes to the annual mean profile shape and its MSL shoreline position. However, there is no assumption that mobile volume changes are equally distributed across a defined active profile as with Bruun (1962). The observations at Cardiff suggest that year-to-year volume changes have a greater impact on the mean shape of the shallower half of what is considered the "Brunn" active profile.

3.3 $\Delta X_{[\ ]}$, Yearly ENSO-driven Beach Width Change

$\Delta X_{El\ Niño}$ [-4 m , El Niño years only] is the magnitude of the ENSO cycle retreat of the annual mean shoreline during an El Niño year (moderate *or* strong) associated with sand that remains within the nearshore zone (as opposed to net zone loss associated with $V_{El\ Niño}$), $\Delta X_{El\ Niño}$ is estimated as the portion of the total 2016 El Niño Cardiff beach width loss (-9.5 m, green line, Fig. 3b) that is not explained by the concurrent net nearshore volume loss (-59K m^3 , green line, Fig. 3a). Using $C_{Equil} = 9.5 \times 10^{-5}$, ΔX from net volume loss = $C_{Equil} \cdot$ -59K m^3 = -5.5 m, and $\Delta X_{El\ Niño}$= -9.5 m − (-5.5 m) = -4 m.

$\Delta X_{Recovery}$ [+0.8 m/yr] is the natural wave-driven recovery of the annual mean shoreline between moderate/strong El Niño winters. This multi-year profile adjustment is caused by shoreward migration of sand from the outer portion of the nearshore zone back to the beach and is based on observed change between 2010-2014 at South Torrey Pines during a recovery period with a stable nearshore volume (red lines, Fig. 3).

3.4 $\Delta Z_{SL} / \beta_{SL}$, Yearly Sea Level Rise Beach Width Change

A landward shift in the shoreline position, $\Delta X_{SL} = -\Delta Z_{SL} / \beta_{SL}$, is applied with each annual time step, where $\Delta \boldsymbol{Z_{SL}}$ is the yearly projected change in mean sea level. The mean annual shoreface slope, β_{SL} , of the shoreline at MSL (~1/50 = 0.02 for Cardiff) is assumed to remain constant as the beach migrates on interannual time scales. This differs slightly from the Bruun (1962) shoreline retreat model, which uses the mean slope of the active profile, not just the shoreface slope around MSL. The sediment budget model is structured to examine active sand management strategies to mitigate for climate change impacts, not to predict the likely extent of inland retreat in cases where a sandy subaerial beach no longer exists or Hwy 101 (backing the dune, Fig. 2) is undermined permanently.

Future MSLR scenarios are based on near-term (2020-2050) estimates from the 2022 NOAA sea level rise for La Jolla (Sweet et al, 2022, Fig. 5). The sea level change term (Eq. 1) for any given year was obtained by piecewise cubic hermite interpolating between the NOAA decadal projections for Relative Sea Level at La Jolla. Each of the NOAA MSLR scenarios, defined by a target global mean sea level in 2100, is based on an ensemble of outcomes from different global climate models and greenhouse gas emission scenarios. Low (0.3 m rise by 2100), intermediate (1.0 m) and high (2.0 m) scenarios were used. Each MSLR scenario is represented by a median (50^{th} percentile) MSLR curve and (17^{th} and 83^{rd} percentile upper and lower bounds (Fig. 5).

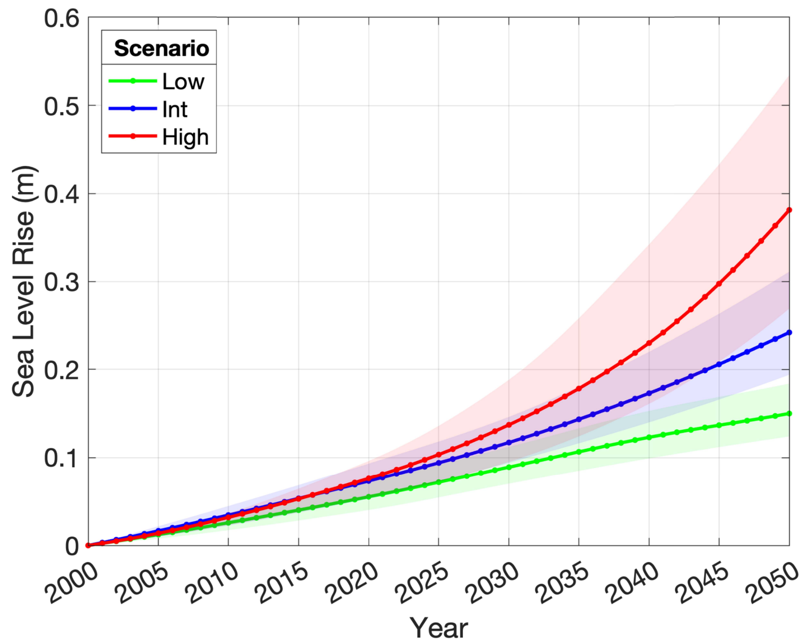

Fig. 5. Three 2000-2050 mean sea level rise (MSLR) scenarios for La Jolla (Scripps Pier), derived from the 2022 NOAA sea level rise technical report (Sweet et al, 2022). Median (50^{th} percentile) values for the Low, Intermediate, and High report scenarios are the solid lines. Individual scenario uncertainty (shaded regions, 17th-83rd percentile range of global climate model outcomes) are included in climatic sediment model projections (Section 5).

3.5 Model hindcast validation

The hindcast X_{MSL} (Eq. 1) for 2000-2019 uses actual bypass rates and nourishment amounts with three El Niño years (Table 1, Fig. 6a), and captures the overall positive trend in observed beach width, and also the beach narrowing during the moderate 2003 and 2010, and strong 2016 El Niños. Before the 2018 San Elijo Lagoon Restoration Project nourishment (SANDAG, 2020) annual bypassing of inlet sand was the dominant contributor to Cardiff widening (blue line, Fig. 6b). Of 230K m^3 in the 2018 nourishment, only about half is apparent in the estimated volumes (Table 1). The La Jolla tide gauge sea level increase for 2000-2020 (0.041 ±0.004 m) is significant with -2.1 m beach width reduction (green line, Fig. 6b), about half the 2016 strong El Niño (-5.6 m, yellow line, Fig. 6b).

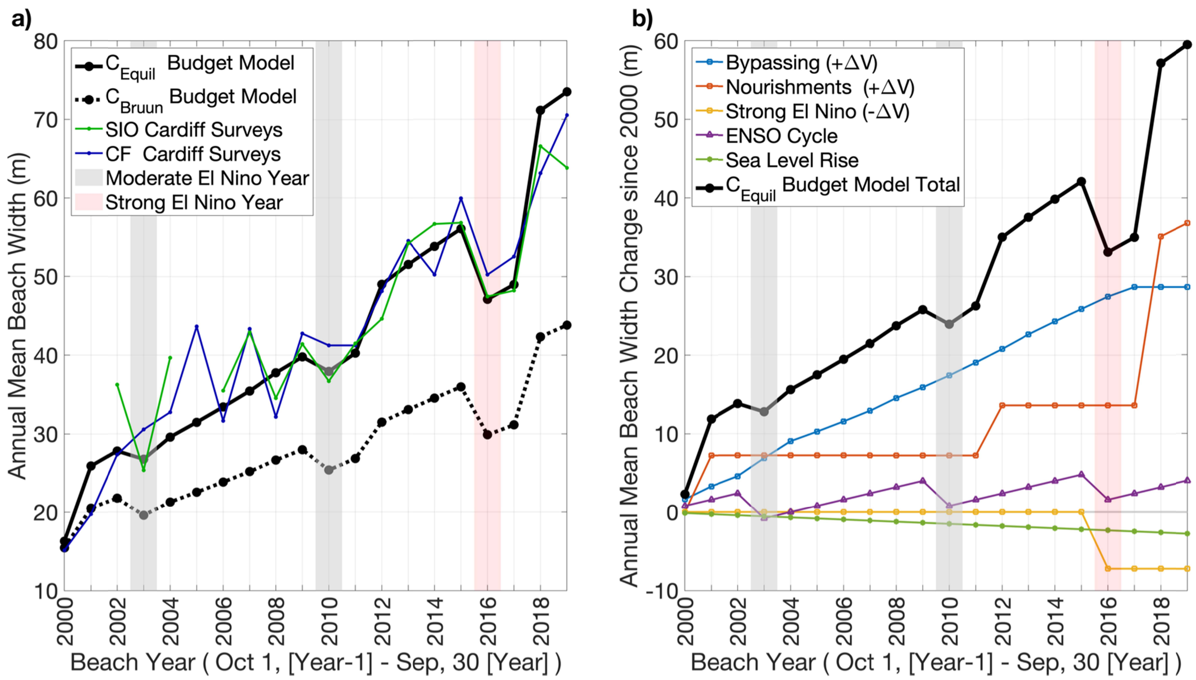

Fig. 6. Cardiff 2000-2019 annual mean beach width observations and predictions. (a) Modeled and observed annual beach width versus time (Eq. 1, with the observation based C_{Equil} and the Bruun (1962)-estimated C_{Bruun}). The model uses nourishment and bypass volumes in Table 1, the fixed model coefficients defined in Sections 3.1.1. – 3.1.4., and the NOAA intermediate median sea level scenario. (b) Contributions of the budget model source/sink terms to the modeled total beach width change at Cardiff since 2000.

4. 2020-2050 Model Projections

4.1. ENSO Scenarios

Two ENSO cycle scenarios are considered in combination with the three MSLR scenarios (Fig. 5). ENSO Scenario 1 assumes continuation of the pattern in recent decades, with El Niños occurring approximately every 6 years, with every 3rd El Niño being strong. ENSO Scenario 2 increases the frequency of strong El Niños from every third El Niño in the 6 year cycle (18 years apart) to every other El Niño (12 years apart) as a representation of the findings of Cai et al. (2021).

4.2. Projection without Future Management

With no further management (bypassing, nourishments, or dune maintenance) projected beach width loss by 2050 ranges from -4 m and -28 m across three MSLR and two ENSO cycle scenarios (Fig 7). Most loss uncertainty is owing to MSLR uncertainty (color shaded zones), with a 2050 beach loss difference between the two El Niño scenarios of only -5 m to -6 m for each median MSLR scenario (comparing solid-colored lines in left and right panels, or the downward shift of the shaded MSLR areas, Fig. 7).

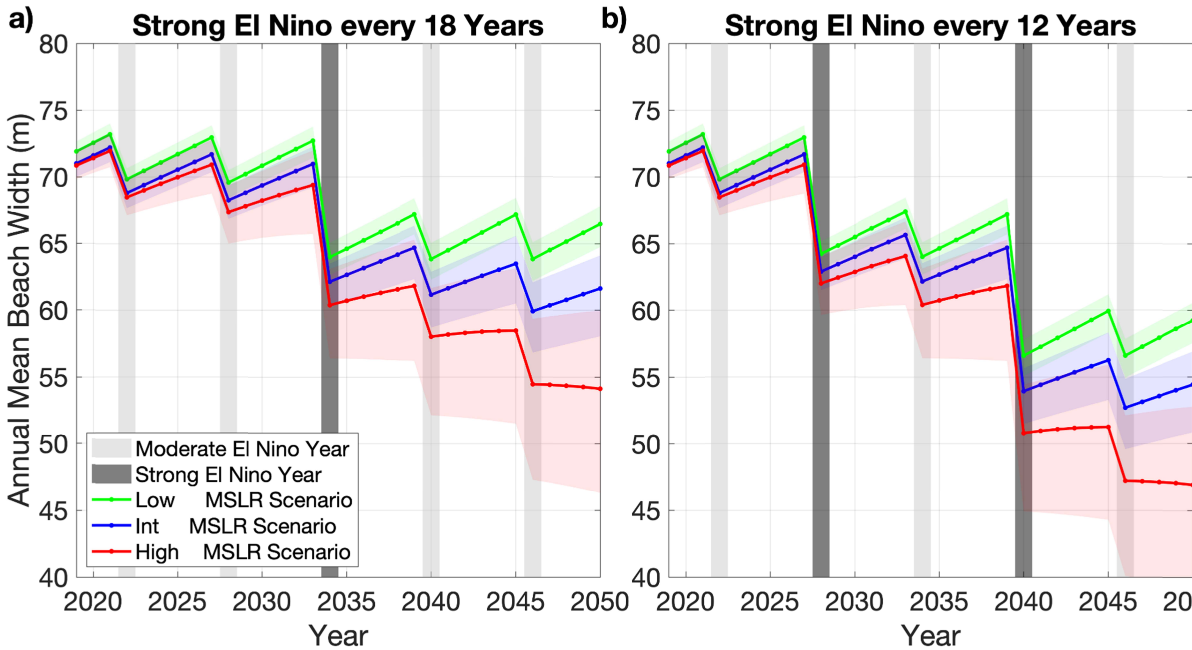

Fig. 7. Projected (Eq. 1) 2019-2050 annual mean beach widths at Cardiff for two ENSO scenarios: a 6-year ENSO cycle with a strong El Niño (a) every 18 years and (b) every 12 years following the strong 2016 El Niño; and for three MSLR scenarios (Low, Intermediate, and High with ranges of uncertainty, see Fig. 5) translated into beach width change.

4.3. Equivalent Sediment Volumes of Projected MSLR Beach Width Loss

When considered with C_{Equil}, the projected MSLR annual mean beach width changes can also be viewed as a loss in wave-driven mobile nearshore sediment volume as the cross-shore profile deepens with MSLR. The equivalent loss in nearshore volume, or inversely, the added yearly sand volume needed to keep up with MSLR, Z_{SL}, is

(4) $$V_{SL} = \frac{Z_{SL}}{C_{Equil}\,\beta_{SL}}$$

The three MSLR scenarios differ substantially (Fig. 8). However, in all cases, the annual sand additions required to mitigate for MSLR are less than or equal to the current bypassing at the San Elijo Lagoon inlet (15K-20K m^3/yr). MSLR is potentially manageable at Cardiff through 2050 using established bypassing methods, assuming current levels of bypassing continue. Cardiff MSLR volume losses (Fig. 8) are roughly half that estimated using Brunn (1962) "Rule" based tables (Flick and Ewing, 2009). Similarly, the observed beach widening with sand bypassing and nourishment from 2010-2015 was about twice a typical Bruun Rule estimate (Fig. 6a).

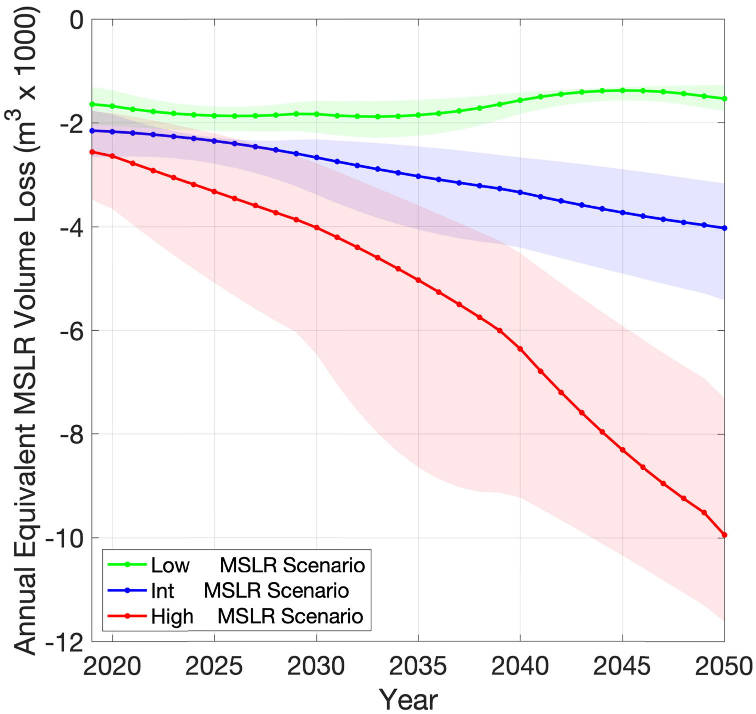

Fig. 8. Estimated MSLR annual equivalent nearshore volume loss versus time at Cardiff with three sea level rise scenarios using Eq. 4. In 2050, as much as ~10K m^3 /yr, or about half the current typical bypassing volume, may be required to keep pace with MSLR. ENSO losses (Fig. 7) are not included. The mild fluctuations of the volume loss curves are an artifact of the underlying MSLR curves being statistical percentiles of an ensemble of different climate model projections as described in section 3.4.

4.4. The 2020-2050 "Hold the Line" Sediment Management Scenarios

The average annual bypass sand required to retain the 2019 beach width as a long-term mean through 2050 (Fig. 9) is in all scenarios less than half the estimated present bypass rate (17K m^3). In each case, the current living shoreline dune (20K m^3) is added to the nearshore budget during the strong El Niño years. This addition is not insignificant as a mitigating factor for the overall sand supply during a strong El Niño winter, as it represents one-third of the estimated $\Delta V_{\text{El Niño}}$ = 59K m^3 of permanent offshore/downcoast sand loss from the system. The bypass volume in the same year is set to zero, assuming the dune is rebuilt using that year's bypass volume (in combination with additional sand from outside the system if necessary to reach the 20K m^3 total).

While the estimated average annual volumes of bypass sand required to hold the line are feasible, the overall range of uncertainty across the combined ENSO and MSLR scenarios (1,400-7,000 m^3) is large. The MSLR scenario uncertainty (fixed ENSO scenario) once again dominates, resulting in annual bypass volume uncertainty of approximately a factor of 2.5 to 3.9, while for the ENSO uncertainty (fixed MSLR scenario) the factor is 1.3 to 2.0. Gopal (2022) used more conservative values for C_{Equil} and $\Delta V_{El\ Niño}$ resulting in hold the line bypass rates that are approximately twice as large as those in Fig. 9, but still well below the historic ~17K m^3/yr average bypass rate.

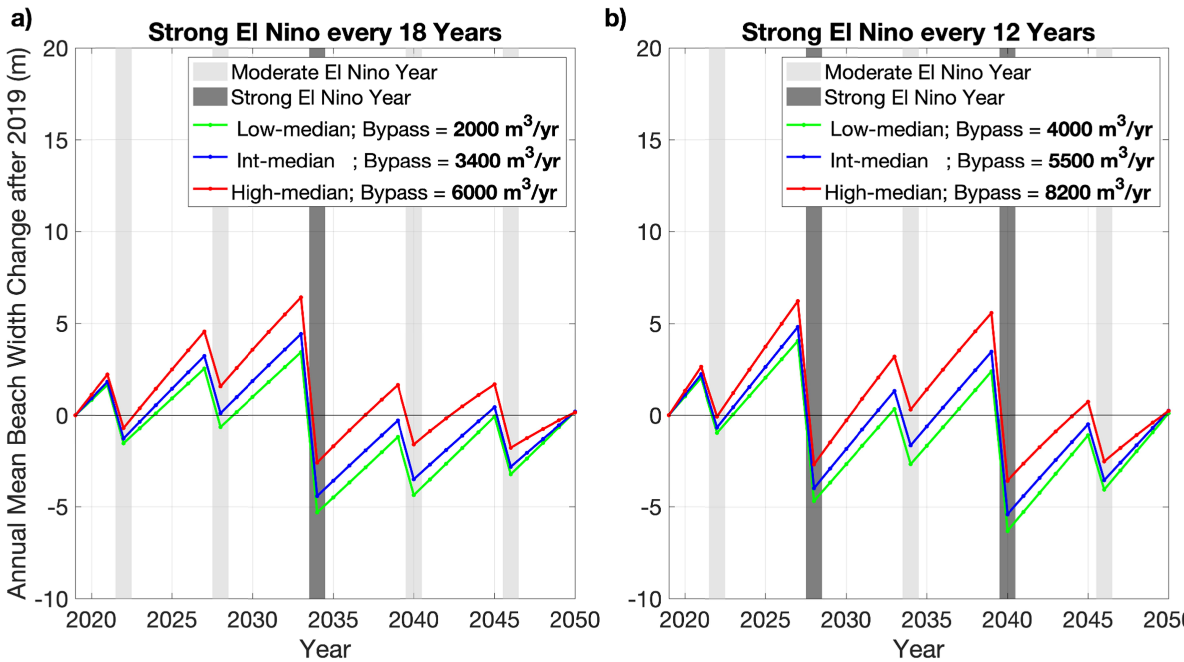

Fig. 9. Estimated annual bypass volumes required (legends) to "hold the line" at Cardiff through 2050 for the two ENSO scenarios and three MSLR scenarios (median sea level rise curve only for each MSLR scenario).

5 Conclusions

Without human added sand, El Niños and MSLR will potentially decrease beach width at Cardiff State Beach by as much as ~25 m by 2050, using the more severe climate scenarios (Fig. 7b). However, our results indicate routine bypassing will be a primary factor for stabilizing, or even increasing, the beach width over the next 30 years. Even reduced annual bypassing of ~10K m^3/yr "holds the line" at Cardiff through 2050 for all scenarios (Fig. 9). In the absence of bypassing, an equivalent nourishment schedule could potentially restore beach width. Engineering analysis of cost, quality of sand, and logistical constraints of nourishment vs. bypassing would determine the preferred strategy. For instance, the nourishment costs at Cardiff were approximately \$25/m^3 of sand during the Regional Beach Sand Project II in 2012 compared with ~\$5/m^3 for yearly dredging (SANDAG, 2021; Gopal, 2022; Leslie, 2022).

The observed interannual mean beach width change with nearshore volume change at Cardiff was about a factor of two higher than predicted with the Bruun (1962) Rule using typical estimates of the active profile closure depth (Fig. 6a, S2). The Bruun approach significantly underestimated the +/- changes in observed beach width when initialized with observed +/-

changes in the nearshore volume at Cardiff across a full La Niña/El Niño climate cycle (2010-2016). Compared to the Bruun-based ratio between beach width and nearshore sand volume, the observation-based ratio in the sediment budget model requires larger sand additions to match permanent beach width loss in severe winters (i.e. strong El Niños), but smaller sand additions to keep pace with MSLR-only beach width loss.

The climatic sediment budget model concept is based on historical observations of waves and beach changes in the San Diego region through 2019, which have been linked primarily with ENSO cycle weather patterns (Vos et al., 2023). More recent winters since 2019 suggest that additional climatic weather patterns (eg. years with frequent atmospheric rivers) may result in nearshore volume loss and can be included based on future survey results. Subaqueous surveys to quantify further the losses from the nearshore zone to deep water and alongshore (over reefs) are ongoing.

The 2010-2016 observations of nearshore sand volume changes at Cardiff indicate that sand stored in the living shoreline dune could play a significant role in future annual beach width resilience after severe erosion events. For example, if the entire dune is eroded, it would mitigate for approximately one-third of the nearshore sand volume that was estimated to be permanently lost from the system during the strong 2016 El Niño. However, more recent winter storm damage to the dune shows that the dune volume change term in the sediment budget equation will need to be invoked more frequently. Damage to the dune toe during a singular extreme wave event in January 2021 (Fig. 2) was repaired with 5,000 m^3 of the bypassed sand from San Elijo Lagoon, with the remainder of the bypassed material placed in the intertidal zone of the beach. Energetic waves associated with a series of atmospheric river weather events partially eroded the dune again in January 2023. The interplay between dune restoration and beach placement of bypassed sand will be a key consideration in future adaptive management efforts.

The Cardiff sediment budget model assumes that the MSL shoreline location is predominantly sandy, which remains true even for the "no further management" scenario that projects sandy shoreline retreat through 2050. Cobbles are not accounted for but are frequently observed at Cardiff (Matsumoto et al. 2020). They were used in the construction of the living shoreline dune (Winters et al. 2020) and largely covered the severely eroded January 2023 beach (not shown). The influence of cobbles on long-term beach change is still unknown.

The proposed shoreline retreat model is structured to examine active sand management strategies to mitigate climate change impacts, not to predict the likely extent of any new landward erosion. The budget model is part of the ongoing monitoring and prediction of California State Beach changes updated annually using current beach surveys and government climate and MSLR projections. The overall benefits of annual bypassing are clear. An annually managed beach reduces the environmental impacts associated with larger and more costly episodic sand placements and ensures an increased recovery rate of beach width after an El Niño or other erosive winter. Ongoing observations, particularly of winters with severe erosion, will enable further model calibration and increased confidence in model projections.

Acknowledgments

Support from U.S. Army Corps of Engineers (W912HZ1920020) and California Department of Parks and Recreation, Division of Natural Resources Oceanography Program (C19E0026) is gratefully acknowledged. Thank you to the many who provided the foundation for this work with 20+ years of data collection and curation - including the field crew, lifeguards, surfers, city managers, SIO administrators, the Coastal Data Information Program, SANDAG, and numerous additional partners.

Open Research

Datasets for this research are included in this paper (and its supplementary information files).

Beach report datasets are also available at the Coastal Processes Group repository here:

https://siocpg.ucsd.edu/data-products/beach-report-guide/beach-report-2022/br-cardiff-2022/cardiff-beachwidth-2022/

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Supporting Information for

A Climatic Sand Management Model for Cardiff State Beach, CA

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Figures S1, S2

Introduction

The supporting information provides equations and datasets that form the basis of the models outlined in the manuscript. The figures included here are examples of surveyed data for Cardiff, and how the observed beach changes relate to the Bruun rule.

Text S1. Cardiff Nearshore Sand Retention

Surveys of Cardiff from 2011-2015, between El Niños, show a significant increase in sediment volume that was equal to the reported additions to the beach by annual inlet bypassing and a beach nourishment project (Fig. 3, Table 1). This suggests that during non-El Niño years Cardiff can be approximated as either a static closed system or a dynamic sediment reservoir (or capacitor) with equal amounts of sediment naturally entering the system in the north and exiting in the south, independent of the human sand additions. Either scenario provides a useful basis for a data-driven climatic sediment budget model for the area.

Plausible explanations for sand retention at Cardiff include reefs at the southern boundary acting as a sand weir, limiting the southward annual drift through the area during non-El Niño years (Fig. S1), combined with weak annual wave-driven alongshore transport forcing seaward of the lagoon (Fig. S2).

It is generally accepted that waves move sand southward along the northern San Diego County coastline on interannual timescales, a process often referred to as the Oceanside Littoral Cell "river of sand" (Inman and Shelton, 1967; Patsch and Griggs, 2006). However, this southward migration of sand is likely episodic owing to the ENSO climate cycle that strongly influences the local winter wave climate (Smith and Barnard, 2021, Vos et al., 2023).

The SIO Coastal Data Information Program (CDIP) Monitoring and Prediction (MOP) system (O'Reilly et al., 2016) provides hourly hindcasts of nearshore wave heights (H_S) and radiation stresses (S_{xy}) for sites roughly 100 m apart on the 10-m depth contour along the Cardiff coastline. A widely used formula for longshore transport is the CERC equation (Shore Protection Manual, 1984; Seymour and Higgins, 1978). The transport rate (Q) is proportional to the square root of significant wave height times the longshore wave radiation stress:

(A.1) $Q = K \cdot \sqrt{H_s} \cdot S_{xy}$,

where the coefficient K is a function of grain size.

Leaving K as an unknown and summing a time series of hourly MOP Q values over a beach year yields a net annual *relative* transport rate at each alongshore site. Annual relative transport rates at Cardiff for the 2011-2016 beach years (Fig. S2) show a trend of decreasing southward annual transport in front of the lagoon and a mild (small positive) net transport reversal near Seaside Reef.

S_{xy} estimates in 10-m depth are considered valid in the actual shoreward littoral transport zone for the case of a simple planar beach (Longuet-Higgins, 1964). Therefore, the transport estimates at Cardiff are more qualitative owing to the complexity of the nearshore bathymetry around the reefs. Nevertheless, lower annual southward transport values are predicted in the vicinity of all the (less complex) coastal lagoons in the region and this may contribute to multi-year time periods of sand retention at Cardiff.

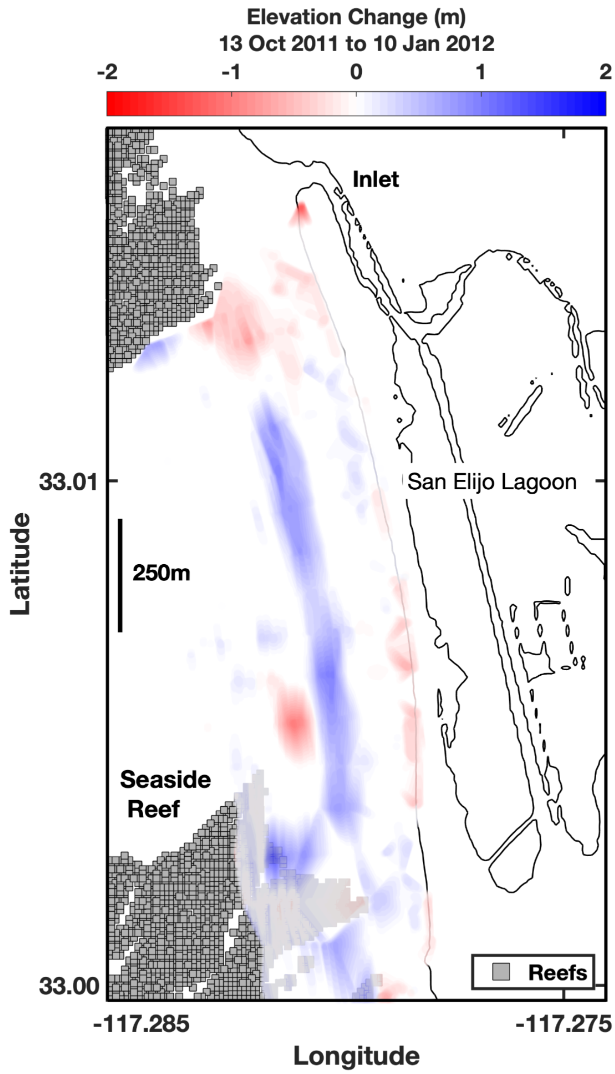

Figure S1. Example surveyed winter sand erosion and deposition pattern at Cardiff in the non-El Niño winter of 2012. Significant sand deposition (blue) occurs around the elevated Seaside Reef (gray area, bottom of figure), a physical barrier to southward drift, as is Tabletop Reef further to the south (Fig. 1c).

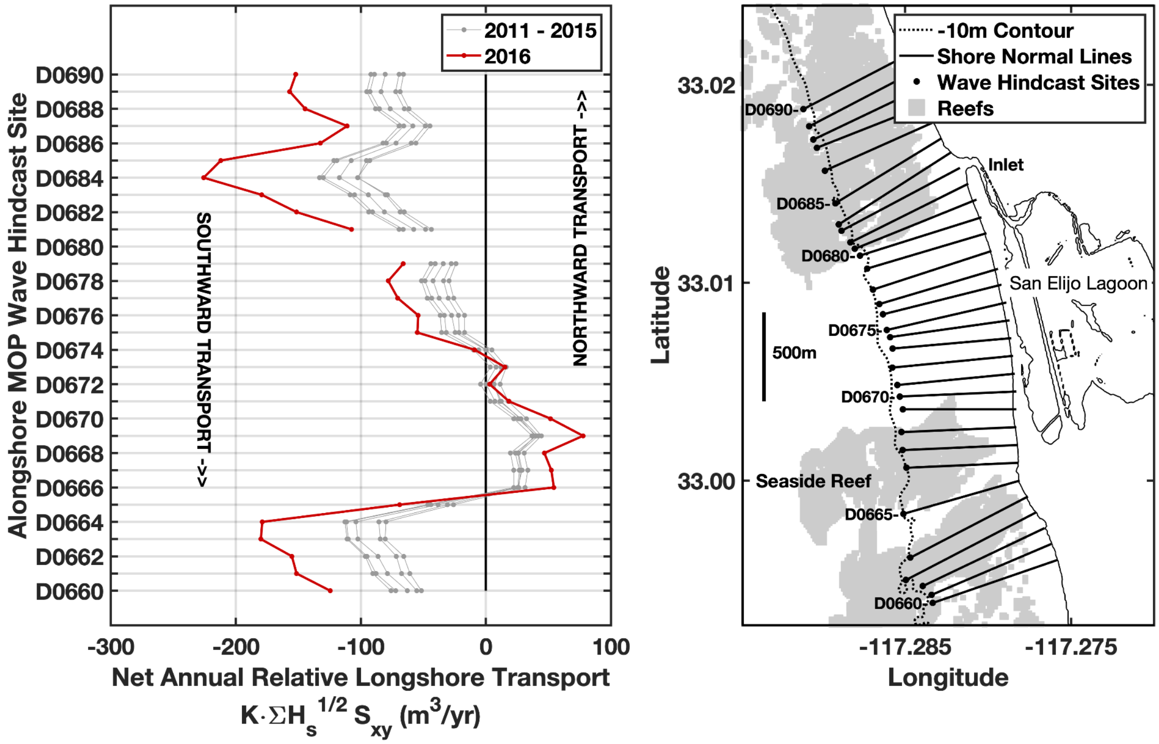

Fig. S2. 2011-2016 wave-driven net annual relative sediment transport for the Cardiff coastline from the CDIP MOP system. In the non-El Niño beach years from 2011-2015 (gray lines, left panel), southward transport slows in front of the lagoon (right panel), with a mild northward (positive) transport reversal near Seaside Reef. During the strong El Niño wave winter in 2016 net southward transport was enhanced significantly (red line). The wave hindcasts are in 10 m depth and not influenced by the shallower portions of the reefs that physically block longshore sand migration (Fig. S1).

Text S2. Observed Beach Changes vs. The Bruun Rule

The Bruun (1962) Rule for MSLR-driven shoreline recession is:

(B.1) $\Delta X_{MSL} = \Delta Z_{SL} \cdot L \,/\, (h + B) = \Delta Z_{SL}/\beta_{AP}$,

where ΔZ_{SL} is sea level rise, L = horizontal length of the "active profile" from the "closure depth" (h) to the berm top height (B). The active profile has height (h+B) and mean slope

$\beta_{AP} = (h + B) \,/\, L$. As sea level rises, L (and β_{AP}) can change depending on the inland profile elevation and erodibility. For the idealized case of both instantly erodible and conveniently β_{AP}-sloped inland geomorphology, L and β_{AP} remain constant with sea level rise and the present active profile shape elevates and shifts inland (Eq B.1).

The Bruun Rule is oversimplified (Cooper and Pilkey, 2004) but is nevertheless widely used. Large sources of uncertainty in applying Eq. B.1 are the true erosion rates of the inland geomorphology (if not sand) and the length L of the hypothetical, conceptual equivalent "active profile". Alternatively, the Bruun Rule can be used to estimate the volume of added sand needed to "keep pace" or "hold the line" with MSLR (ΔX_{MSL} = 0),

(B.2) $\Delta V_{MSLR} = \Delta Z_{SL} \cdot L = \Delta Z_{SL} \cdot (h + B)/\beta_{AP}$,
where ΔV_{MSLR} has units of m^3/m of shoreline.

Eqs. B.1 and B.2 can be (inversely) used to predict beach widening with added sand volume and constant sea level. That is, the Bruun Rule ratio of beach width to beach volume change,

(B.3) $C_{Bruun} = \Delta X / \Delta V = [\, \Delta Z_{SL} \cdot L \,/\, (h + B) \,] \,/\, [\, \Delta Z_{SL} \cdot L] = 1 \,/\, (h + B)$
where ΔX has units of m and ΔV has units of m^3/m of shoreline. C_{Bruun} depends only on the active profile height (independent of profile slope). A wide range of equivalent closure depths could be used at Cardiff. Here we use a depth range of 8-20 m depth and a berm height of 2 m, yielding C_{Bruun} = 0.045 to 0.10 m of beach width increase for each 1 m^3/m of shoreline of added sand.

Using observations between El Niños from 2010-2015 (ΔX=15 m, ΔV=158K m^3/1,700 m of shoreline, Section 3.2),

(B.4) $C_{Observed} = 0.16$, and the ratio $C_{Observed}/\, C_{Bruun}$ is between 1.5 and 3.5.

Similarly, the estimated strong El Niño permanent beach narrowing from 2015-2016 (-5.5 m attributed to the net -59K m^3 loss of nearshore sand (Section 3.3) is underpredicted by Bruun (1962) (-1.6 m to -3.5 m). The estimated sand additions required to keep up with sea level rise (Fig. 8) are between 0.3 and 0.6 of a Bruun based estimate (Flick and Ewing, 2009).